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Review

Environmental risk assessment of pesticides in tropical terrestrial ecosystems: Test procedures, current status and future perspectives

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ABSTRACT

Despite the increasing use of pesticides in tropical countries, research and legislative efforts have focused on their temperate counterparts. This paper presents a review of the literature on environmental risk assessment of pesticides for tropical terrestrial agroecosystems. It aims at evaluating potential differences in pesticide risk between temperate and tropical regions as well as to highlight research needs in the latter. Peculiarities of pesticide risks in tropical terrestrial agroecosystems are discussed in subsections 1) agricultural practices; 2) research efforts; 3) fate and exposure; 4) toxicity testing methods; and 5) sensitivity. The intensive and often inadequate pesticide application practices in tropical areas are likely to result in a relatively greater pesticide exposure in edge-of-field water bodies. Since pesticide fate may be different under tropical conditions, tropical scenarios for models estimating predicted environmental pesticide concentrations should be developed. Sensitivity comparisons do not indicate a consistent similar, greater or lower relative sensitivity of tropical soil organisms as compared to temperate organisms. However, several methods and procedures for application in the tropics need to be developed, which include: 1) identifying and collecting natural soils to be used as reference test substrates in tests; 2) identifying and discerning the range of sensitivity of native test species to soil contaminants; 3) developing test guidelines applicable to tropical/subtropical conditions; and 4) developing methods and procedures for higher tier testing for full development and implementation of environmental risk assessment schemes.

1. Introduction

The intensification of agricultural practices in tropical areas has led to an increasing use of pesticides over the past decades (Albuquerque et al., 2016; Daam and Van den Brink, 2010; Lewis et al., 2016). For example, in Brazil, which is one of the largest consumers of pesticides in the world, there has been an increase of 134% in pesticide sales from 2000 to 2014 (Bombardi, 2017).

While in North America, Europe, and other countries like Japan and Australia, a well-established legal framework for pesticide environmental risk assessments exists, such requirements are either not available, unclear or inadequately implemented and applied in tropical countries (Albuquerque et al., 2016; Niemeyer et al., 2017; Niva et al., 2016). Therefore, the increase in pesticide use has not been properly followed with the development of studies and specific legislation to assess their environmental effects in tropical countries (Chelinho et al., 2012; Eijsackers et al., 2014; Oliveira et al., 2018). Also, cheap compounds that are environmentally persistent and highly toxic, are today banned from agriculture use in developed countries, but remain popular in developing countries (Carvalho, 2006). For example, acephate and atrazine, which are banned in the European Union (EU), are the top 3 and 7 pesticides sold in Brazil, respectively (Bombardi, 2017). The risks of pesticide application to both humans (applicators and consumers) and the environment are often aggravated by the lack of

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training of pesticide applicators (Niemeyer et al., 2017; Niva et al., 2016; Waichman et al., 2007). Subsequently, both soil and aquatic contamination with residues from pesticides is an increasing problem in the tropics (Carvalho, 2017).

Tropical areas harbor the greatest biodiversity in the world and generate nearly 60% of its primary productivity (Deshmukh, 1986). This greater species richness, as compared to their temperate counterparts, dictates that the possible occurrence of more sensitive species cannot be ignored (Castillo et al., 2015; De Silva and Van Gestel, 2009a; De Silva et al., 2010b; Lacher and Goldstein, 1997; Niemeyer, 2012). In addition, due to differences in the agroecological conditions between these climatically distinct areas, it has long been acknowledged that pesticide fate as well as the exposure route and toxic action in organisms may also be expected to be quite different under tropical conditions (Daam and Van den Brink, 2010; De Silva and Van Gestel, 2009a; Laabs et al., 2002a; Viswanathan and Krishnamurti, 1989).

The aim of the present paper is to review the literature on environmental risk assessment of pesticides conducted in tropical terrestrial agroecosystems, to address potential differences between temperate and tropical systems as well to highlight the improvements needed in test procedures and research. Regarding the organism groups covered, we confined ourselves to soil invertebrates, because other soil organisms, in particular microbes and fungi, considerably differ from animals in terms of test methodology as well as in their response to environmental variables. In the present study, those countries listed in IUCN (1986) of having at least half of their land mass between the Tropics of Cancer (23° N) and Capricorn (23° S) were considered as tropical (after Daam and Van den Brink, 2010). Climatic regions or zones may display site-specific features on the meso- and micro-scales, i.e. climates that differ from the regional average because of special terrain or relatively local effects of the atmosphere (McKay and Thomas, 1989). Besides latitude (i.e. 23° N–23° S), altitude should be considered when considering tropical climates (Dussart et al., 1984). Although these factors are acknowledged, it is neither feasible nor practical to discuss all possible terrestrial ecosystems worldwide on a micro-scale. Therefore, we confined our study to general trends and peculiarities of pesticide risks in tropical terrestrial agroecosystems and discuss these in the following subsections: 1) agricultural practices; 2) research efforts; 3) fate and exposure; 4) toxicity testing methods; 5) sensitivity; 6) the way forward.

2. Agricultural practices

In their review on aquatic tropical pesticide ecotoxicology, Daam and Van den Brink (2010) indicated several agricultural practices that may lead to a greater pesticide exposure under tropical conditions. Practices also relevant for tropical terrestrial agroecosystems include i) unnecessary applications and overuse; ii) use of cheaper but more hazardous pesticides, and iii) dangerous transportation and storage conditions, all often a result of a lack in training of pesticide applicators and legislation in the tropics (Daam and Van den Brink, 2010 and references therein). These are hence only briefly discussed here in view of their implications for tropical terrestrial (in particular soil) risk assessments.

In tropical countries, pesticides have often been reported to be applied at a high frequency and throughout a large part of the year (e.g. Albuquerque et al., 2016; Lewis et al., 2016; Rasmussen et al., 2016). According to Racke et al. (1997) this may be partially due to the aggressive nature of some tropical pests and perhaps partially due to the harsh environmental conditions that may be present in tropical environments, resulting in more frequent incidences of insect pests and plant diseases and lowered pesticide efficacy. For example, applications of soil insecticides for termite control, which provide 10–20 years of efficacy in temperate zones, often only provide 2–5 years of control under tropical conditions (Racke et al., 1997). This lower pesticide efficiency in tropical areas is often counteracted by increasing pesticide application dosages and frequencies (Rerkasem, 2005).

More frequent pesticide applications may hamper recovery of affected populations of soil organisms, leading to chronically altered soil communities with a dominance of insensitive species. Tropical soil organisms may have longer life-cycles and more extended breeding seasons than their temperate counterparts (e.g. the tropical earthworm *P. corethrurus*; Buch et al., 2011, 2013, as well as tropical isopods in general; Ockleford et al., 2017). In addition, high frequency of applications may dictate that the likelihood of pesticide mixture exposures (and hence their potential additive or synergistic effects) is also greater (e.g. Moreira et al., 2017; Vig et al., 2008). Future studies are hence needed to evaluate the effects of environmental realistic pesticide mixtures in tropical settings. Besides directly resulting from pesticide applications, the way pesticide products are handled, and the disposal of tank residues, may be a great source of soil contamination in agricultural areas. Carniel (2015), for example, indicated a high risk of commonly discarded spray tank residues containing mancozeb and chlorpyrifos to several soil organisms in apple orchard areas in south Brazil.

The pesticide application rates and practices in tropical areas are likely to result in a greater pesticide exposure (and hence risk) in real-world agricultural settings than in their temperate counterpart. In the remaining parts of this paper (from section 4 onforwards), possible differences in pesticide risk between temperate and tropical agroecosystems considering the same pesticide use pattern are evaluated. This was done to deduct which parameters may underlie possible differences in pesticide fate and effects in these climatically-distinct areas and which implications they may have on risk assessment procedures to be adopted in tropical areas.

3. Research efforts

Despite that research on pesticide ecotoxicology in tropical areas has increased in recent years, it has been focused mainly on the aquatic compartment (Chelinho et al., 2012; De Silva and Samayawardehena, 2005; Niemeyer et al., 2017; Niva et al., 2016). After evaluating the number of publications on terrestrial ecotoxicology included in Scopus®, it can also be concluded that i) although increasing, the number of contributions from tropical areas stays behind of those seen worldwide; and ii) tropical research has mainly been conducted in tropical Asia and Latin America (Fig. 1). Within these continents, the bulk of the terrestrial ecotoxicology research has been conducted in Brazil (South America; 64 ± 3%) and India (Asia; 62 ± 6%). The latter two countries even make up over half (55 ± 0.4%) of all tropical contributions worldwide in the past 15 years. Subsequently, despite the noticeable progresses, more research is needed to provide clearer insights into the risks related with pesticides in tropical terrestrial ecosystems (Chelinho et al., 2012; Eijsackers et al., 2014; Niemeyer et al., 2017; Niva et al., 2016). This is especially needed in those tropical countries underrepresented in terms of publications and/or with higher percentages of cultivated land.

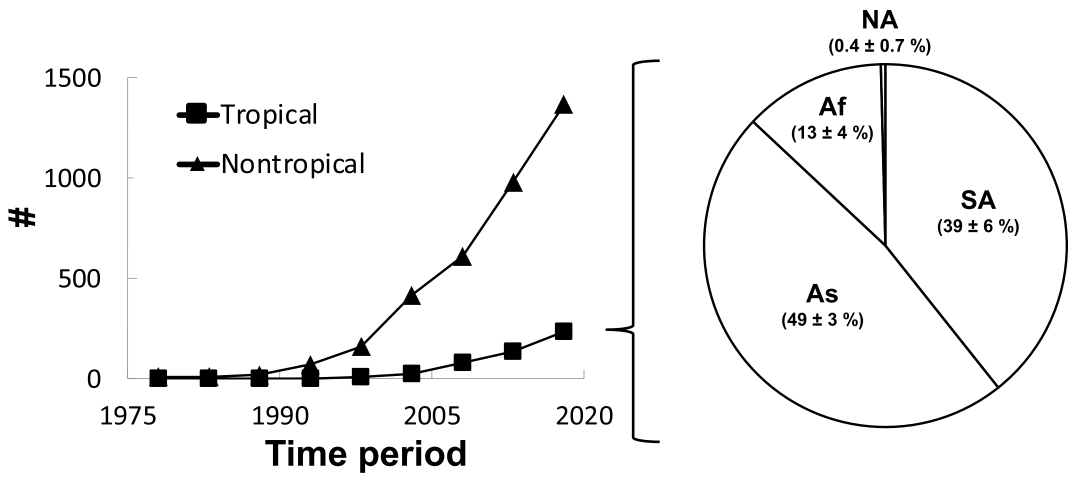

Fig. 1. Dynamics in the number of publications on terrestrial pesticide ecotoxicology calculated in five-year periods since 1974 in tropical and non-tropical regions (left). Countries listed in IUCN (1986) of having at least half their land mass between the Tropics of Cancer and Capricorn were considered as tropical. Only publications fulfilling the search criterion (TITLE-ABS-KEY = ("soil" OR "terrestrial") AND ("ecotoxicology" OR "risk") AND "pesticide") in Scopus (accessed 9 March 2019) were included. The relative contributions of the different continents to the total tropical contributions (mean ± SD) are visualized in the pie chart (right). These percentages were calculated from 2004 onwards since between 1974 and 2003 only a total of 35 publications fulfilled the search criteria for the tropical region. As = Asia; SA = South America; NA = North America; Af = Africa.

4. Fate and exposure

4.1. Pesticide degradation in tropical soils as influenced by temperature and precipitation

Pesticides have often been discussed to dissipate more rapidly from soils under tropical conditions than under temperate conditions (Dores et al., 2009; Laabs et al., 2002a; McDonald et al., 1999; Niemeyer, 2012; Racke et al., 1997; Römbke et al., 2008; Sanchez-Bayo and Hyne, 2011). To illustrate this, the tropical and temperate soil DT50 (degradation or dissipation time 50%) reported in Sanchez-Bayo and Hyne (2011) and Römbke et al. (2008) are shown in Fig. 2. Tropical soil DT50 values were indeed lower than temperate DT50 values in the majority of cases (88% for both herbicides and insecticides) (Fig. 2). Laabs et al. (2002a) reported that DT50 values for most of the pesticides they evaluated were shorter by factors of 5-50 under tropical field conditions than under temperate field conditions. Under laboratory conditions, Laabs et al. (2002b) also noted lower DT50s in tropical soils than those reported from temperate laboratory studies. However, when Laabs et al. (2002b) corrected these DT50 values differences for temperature, the persistence of pesticides in the studied tropical soils was in the same range as reported from temperate soils in laboratory studies. Laabs et al. (2002b) hence concluded that enhanced degradation under tropical field conditions is most likely due to higher temperatures, rather than to specific characteristics of tropical soils. Several other authors also concluded that the most prominent mechanism for the acceleration in pesticide dissipation in tropical soils appears to be related with the effect of higher tropical temperatures, leading to increased volatility and enhanced degradation rates (Förster et al., 2006; Niemeyer, 2012; Racke et al., 1997; Sanchez-Bayo and Hyne, 2011). Shunthirasingham et al. (2010), for example, estimated an increase in degradation and volatilization rates of pesticides by a factor of 2 and 3–4, respectively, for a 10 °C increase in soil temperature. In addition, estimates of the DT50s of photosensitive pesticides indicates that due to more uniform and higher light intensities throughout the year in the tropics, photolytic reactions would be likely to also occur more uniformly and rapidly (Dores et al., 2009; Laabs et al., 2002b; Racke et al., 1997).

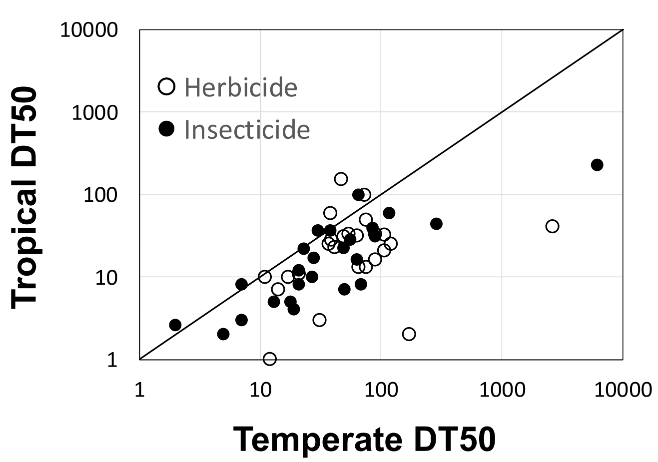

Fig. 2. Temperate (x-axis) versus tropical (y-axis) DT50 values for the dissipation of pesticides from soils taken from Sanchez-Bayo and Hyne (2011) and supplemented with data from Römbke et al. (2008) for those compounds not listed in the former. The diagonal 1:1 line represents the same DT50 values for temperate and tropical conditions. Subsequently, data points falling below and above this line indicate a lower and higher tropical DT50 value (and hence a lower and higher persistence, respectively) as compared to the temperate DT50 value, respectively. DT50 = degradation or dissipation time 50%.

Intensive irrigation practices and episodes of torrential rainfall in tropical areas have often been associated with increased transport of soil contaminants to edge-of-field waterbodies through surface runoff and to groundwater by leaching (Daam and Van den Brink, 2010; Laabs et al., 2002b; Langenbach et al., 2001; Niemeyer, 2012). Langenbach et al. (2001), for example, evaluated the fate of terbuthylazine in Brazilian soils under different climate scenarios in the laboratory and concluded that the high irrigation rate in the simulated Brazilian conditions caused a fast water movement to deeper soil layers. These authors further noted that this rapid displacement of the herbicide from the evaporating surface led to reduced volatilization rates as compared to the temperate scenario (Langenbach et al., 2001). The greater volatilization rates in tropical areas resulting from higher temperatures as discussed above could hence at least partly be counteracted by intensive rainfall and irrigation practices in these areas. Both situations, however, would indicate a faster dissipation from the terrestrial topsoil and hence a less prolonged exposure. On the other hand, greater volatilization rates in tropical areas have been associated with a higher relevance of atmospheric pesticide deposition and hence potential for retransfer to aquatic and terrestrial ecosystems (Daly et al., 2007; Laabs et al., 2002c; Langenbach and Caldas, 2018). Another important source of horizontal contamination of ecosystems is pesticide dispersion due to agricultural spraying (Langenbach et al., 2017). In addition, tropical conditions, e.g., intense rainfalls, often favor runoff, particularly of soluble pesticides (Lewis et al., 2016), which implies a higher exposure potential for surface water organisms including aquatic life stages of insects, but also for adult insects, including pollinators, that drink the water. This chain of interaction indicates how aquatic and terrestrial habitats cannot be considered in isolation from each other, and how knowledge of the life history of organisms is essential in understanding complex interactions among them (Dodds and Whiles, 2010). The relevance of assessing pesticide effects on both soil and aquatic compartments through the evaluation of soil habitat and retention functions has been previously highlighted (Chelinho et al., 2012; Natal-da-Luz et al., 2012), as well as the increased toxicity of pesticide runoff if compared with two other aquatic matrices (leachates and eluates; Chelinho et al., 2012).

4.2. Soil parameters reported to influence tropical pesticide fate

4.2.1. Soil humidity

Higher soil humidity has been associated with faster pesticide degradation and volatilization (Klein, 1989; Römbke et al., 2007; Shelton and Parkin, 1991; Shunthirasingham et al., 2010). When soils become wet after a period of drought, pesticides are lost from the soils through rapid volatilization due to the replacement of the adsorbed pesticides with water molecules (Shunthirasingham et al., 2010). Shelton and Parkin (1991) reported that decreasing levels of soil moisture have consistently been observed to retard or inhibit rates of microbial metabolism, although the pattern or degree of inhibition is dependent upon the substrate, microbial process, and the nature of the soil microflora. These authors further discussed that fluctuations in soil moisture content may affect rates of biodegradation indirectly by affecting the bioavailability of the substrate compound. For example, they noted that concentrations of soluble, and hence bioavailable, carbofuran increased from 15.5 to 25.5 pg/mL with decreasing soil moisture content (Shelton and Parkin, 1991). Similarly, Chelinho et al. (2014) noted a lower toxicity of carbofuran in a soil with a higher moisture content and attributed this to increased degradation and greater dilution of the pesticide in the soil pore water. In another study with carbofuran, Ferreira et al. (2015) studied the bioavailability and the effects of radio-labelled carbofuran on the avoidance behavior, growth and reproduction of *Eisenia andrei* in two natural tropical soils, covering almost the same range of soil properties as in the previous study. These authors explained the different toxicity with the lower organic matter (OM) content in the soil where the worms were more affected.

4.2.2. Clay content

In line with the above, slower pesticide degradation of pesticides in wet soils is usually explained from inactivation of aerobic soil microbes responsible for their degradation (Chai et al., 2010; Racke et al., 1994; Yen et al., 2000). In air-dry soil, an accelerated degradation by clay-catalyzed hydrolysis has been reported for chlorpyrifos (Racke et al., 1994) and acephate (Chai et al., 2010). The types and properties of clay minerals are much more varied in the tropics than in glaciated temperate areas (Racke et al., 1997; Sanchez, 1976). For example, Langenbach et al. (2001) reported a predominance of kaolinite as compared to montmorillonite clay constituents in deeply weathered tropical and nonweathered temperate soils, respectively. To what extent this may imply a general difference in clay-catalyzed hydrolysis and hence degradation in dryer tropical soils requires further study. On the other hand, Laabs et al. (2002b) did not find any substantial influence of contrasting clay contents of different tropical soils (13% versus 47% clay) on the dissipation dynamics of the studied pesticides.

4.2.3. pH

Acidic soils contribute to a greater desorption and hence exposure and persistence of polar herbicides as compared to alkaline or neutral soils (Sanchez-Bayo and Hyne, 2011). Degradation rates are also known to be often affected by prevailing pH levels. Laabs et al. (2002b), for example, related a greater and lower persistence of endosulfan and triazines to an acidic reaction of the studied tropical soils (pH 4–5; 1 M KCl), leading to an enhanced and slower degradation, respectively. However, after reviewing tropical and non-tropical studies on the environmental risks of pesticides, Sanchez-Bayo and Hyne (2011) noted that tropical soil pH in these studies were acidic in 59% of the cases studied, with the remainder being alkaline (23%) or neutral (18%). They further concluded that acidic soils are common in Brazil and Southeast Asian countries; soils from some African countries and Caribbean islands tend to be neutral, whereas those from the Indian subcontinent are alkaline in most cases (Sanchez-Bayo and Hyne, 2011). Subsequently, a possible effect of pH on pesticide fate in tropical soils depends on the geographical (local) conditions and may differ between in-field and off-field areas.

4.2.4. Soil organic carbon content and pesticide Koc

Tropical soils have been considered to be rather deficient in organic carbon (OC) because of the intense microbial degradation that takes place uninterrupted throughout the entire year, whereas soils in temperate regions are rich in OC because their microbial activity is restricted only to the warm seasons (Langenbach et al., 2000; Sanchez-Bayo and Hyne, 2011). This relatively low OC content would hence imply a limited binding capacity of most tropical soils for pesticides (Shunthirasingham et al., 2010). This would suggest a higher bioavailability of pesticides in tropical soils. Since lower soil OC contents also imply a greater pesticide mobility through runoff and leaching, available (i.e. dissolved) pesticide residue levels may, however, more rapidly decline leading to reduced exposure of tropical soil organisms. In addition, this would also influence the pesticide exposure via ingestion of dead organic material on which many edaphic organisms feed, although this has been suggested already (Oliveira et al., 2018).

It is questionable, however, whether tropical agricultural soils contain consistently lower OC contents than their temperate counterparts. Although the rate of organic decomposition is five times greater in the tropics, annual addition of organic carbon to the soil is also five times greater in tropical udic environments than in temperate udic environments (Racke et al., 1997; Sanchez, 1976). But the type of organic matter (OM) and its carbon content (typically about 58% for temperate soils) may differ between tropical and temperate regions. Sanchez-Bayo and Hyne (2011) discussed that a large proportion (58%) of the tropical soils tested in the studies they reviewed had normal OC contents (i.e., between 1.5% and 3%). In addition, these authors indicated that about 45% of the herbicides and fungicides examined showed higher Koc (sorption constant for binding to organic carbon) values than they normally have in soils from temperate regions. Especially in the case of insecticides, this would indicate a trend towards stronger adsorption onto tropical soils, with 77% of the compounds showing slightly higher Koc values, although none of them to a significant extent (Sanchez-Bayo and Hyne, 2011).

4.2.5. Anion exchange capacity

Anion exchange is more likely to occur in tropical soils since they contain significant higher quantities of positively charged adsorption surfaces in the form of aluminium and iron (hydr)oxides than in temperate soils (Langenbach et al., 2001; Kay and Brown, 2006; Racke et al., 1997; Sanchez, 1976). Anion exchange is known to play a significant role in the adsorption of several pesticides (Berglöf et al., 2002; Kay and Brown, 2006; Hyun et al., 2003). Hyun and Lee (2004), for example, demonstrated that anion exchange of prosulfuron accounted for up to 82% of the overall sorption in the pH range 3–7. These authors further concluded that since both hydrophilic and hydrophobic sorption of prosulfuron decreased with increasing pH, addition of fertilizer and lime amendments may enhance the potential for off-site leaching of recently applied acidic pesticides.

4.2.6. Conclusions on the influence of tropical soil characteristics on pesticide fate

From the above, it appears that there are no inherent differences in pesticide fate due to soil properties uniquely possessed by tropical soils, as it has been concluded by several other authors (Kamoun et al., 2018; Langenbach et al., 2000; Natal-da-Luz et al., 2012; Racke et al., 1997). Tropical soils themselves defy easy categorization, and their properties are as varied in nature as those from temperate zones (Racke et al., 1997; Römbke et al., 2008). In the literature there is also consensus that DT50 values can easily differ by a factor of 10 for the same compound applied in the same climatic zone but on different soils (Racke et al., 1997; Römbke et al., 2008).

The exposure of soil organisms to pesticides depends on the regional characteristics of the soils, rather than on climatic characteristics of the tropics (Kamoun et al., 2018; Sanchez-Bayo and Hyne, 2011). Such influence evidently also depends on pesticide properties and may for example be greater for those depending on aerobic microbial degradation (e.g., in the case of abamectin; De Oliveira Ferreira et al., 2016; Dionisio and Rath, 2016). This thus highlights the importance of considering local environmental conditions (including properties of local soils) when evaluating pesticide risks in natural systems (Kamoun et al., 2018; Natal-da-Luz et al., 2012; Niva et al., 2016).

4.3. Need for tropical pesticide fate scenarios

As stated before, soil parameters such as OM or OC content, structure and texture have similar effects on pesticide distribution and degradation globally (Correia et al., 2007; Langenbach et al., 2001). However, local characteristics are strongly influenced by climatic conditions, so knowledge of pesticide dynamics obtained under temperate conditions may be of limited value for predicting pesticide fate in tropical regions (Correia et al., 2007; Langenbach et al., 2001; Reichenberger et al., 2002).

In Europe, the prospective exposure assessment of pesticide uses computer simulation models for ten different agricultural field scenarios, which collectively represent agriculture in the EU (FOCUS, 2001). Given the above, and as has been discussed by many authors, it may be concluded that these scenarios are of little relevance for tropical agroecosystems (e.g. Daam and Van den Brink, 2010; Natal-da-Luz et al., 2012; Racke et al., 1997; Römbke et al., 2008). Reichenberger at al. (2002), for example, discussed that pesticide displacement in a tropical soil reached deeper layers than that simulated for these compounds with the leaching model PEARL. Time-varying pesticide sorption coefficients in tropical field soils also appeared not to be adequately incorporated in existing FOCUS models (Laabs and Amelung, 2005). Typical tropical crops such as pineapple and banana are also not included in existing FOCUS fate scenarios (Natal-da-Luz et al., 2012). However, for banana plantations, a model for pesticide estimation in both soil, water and plants has been recently developed in Costa Rica (Mendez et al., 2018). The need for studies validating environmental fate models and scenarios for application to the simulation of pesticide dissipation and mobility under tropical conditions has therefore long been recognized (Daam and Van den Brink, 2010; Natal-da-Luz et al., 2012; Racke et al., 1997; Römbke et al., 2008).

On the other hand, it is neither financially nor practically feasible to develop fate scenarios for a large number of pesticides and different localities (Brock et al., 2008; Daam and Van den Brink, 2010). Subsequently, in line with the ten FOCUS scenarios used in Europe, a selection of tropical scenarios should be developed to cover the range of tropical agroecosystem conditions. Some recent progress has been achieved for estimating the pesticide risk in the tropics but were mostly focused on the aquatic compartment (Lewis et al., 2016 and references therein; Mendez et al., 2018; Rasmussen et al., 2016). Even though, the lack of both monitoring and ecotoxicological data was highlighted (Lewis et al., 2016).

Table 1
Main soil properties of three typical Brazilian agricultural soils (modified from De Sousa and de Andréa, 2011). WHCmax = maximum water holding capacity; OM = organic matter; N = nitrogen.

Parameter/soil	Typic Hapludox	Mollic Hapludalf	Typic Humaquept
pH (−)	4.7	6.0	4.1
WHCmax (L/kg dry soil)	0.62	0.41	1.43
OM (%)	4.0	4.1	13
N (g/kg)	2.8	3.0	7.0
Clay (%)	63	48	60
Silt (%)	14	18	33
Sand (%)	23	34	7

Racke et al. (1997) discussed that given the relative uniformity of temperature in the tropical zone, differentiation within the tropics is largely due to differences in the amount and distribution of precipitation. Based on this, these authors indicated three fairly distinct tropical zones that can be delineated by moisture regime, which may hence form the basis for the development of different tropical scenarios (Racke et al., 1997). In terms of standardizing soil characteristics for tropical scenario development, the Brazilian Institute of Environment and Natural Resources (IBAMA) has already established three agricultural soils which characteristics cover the main causes of differences in pesticide behavior (Table 1; De Sousa and de Andréa, 2011; IBAMA, 1996).

Field studies in tropical farms measuring pesticide concentrations and relevant environmental parameters for such models and scenarios are urgently needed to evaluate a set of tropical fate scenarios (Daam and Van den Brink, 2010). It may be especially pertinent to include parameters for which the influence and variation are still relatively poorly known. For example, studies evaluating acidic pesticide behavior on variable-charge tropical soils are required to improve tropical pesticide fate predictive models (Hyun et al., 2003).

5. Toxicity test methods

Given the vast differences in physical and chemical environmental parameters between temperate and tropical regions, the use of techniques and procedures developed for temperate environments to assess pesticide risk in tropical risk areas has often been disputed (Lacher and Goldstein, 1997; Niemeyer, 2012; Niemeyer et al., 2017). Recently, Niemeyer et al. (2017) identified four research needs for tropical methods and procedure development, which are further discussed in the following subsections: 1) identifying and collecting natural soils to be used as reference test substrates in tests; 2) identifying and discerning the range of sensitivity of native test species to soil contaminants; 3) developing test guidelines applicable to tropical/subtropical conditions; and 4) developing methods and procedures for higher tier testing for full development and implementation of environmental risk assessment schemes. According to a new paper of these authors at least the last issue (i.e. developing adapted higher tier tests) as well as the implementation of screening tests in environmental risk assessment (ERA) procedures is already under way (Niemeyer et al., 2018b). One additional issue has already (partly) been clarified: for the reference substance boric acid (nowadays used in almost all invertebrate tests recommended by the International Standardization Organization (ISO), but less by the Organization for Economic Co-operation and Development (OECD)) the respective range of test results gained under tropical and temperate conditions seems to be comparable, but this needs confirmation for other chemicals. It also has to be assured that the OM content is similar when comparing temperate and tropical results of testing reference substances (Niemeyer et al., 2018a).

5.1. Tropical artificial soil and natural soils

As the OM component of the artificial OECD soil (OECD, 1984) is neither available or representative of tropical soils, several alternative OM sources have been tested during the development of tropical artificial soil (TAS). Those included xaxim (i.e. fiber material extracted from the trunk of the tree fern *Dicksonia sellowiana*), paddy husk, sawdust, non-composted and composted coco peat (De Silva and Van Gestel, 2009a; Garcia et al., 2011). Composted coco peat has generally been concluded to be the most suitable replacement for sphagnum peat in TAS (De Silva and Van Gestel, 2009a; Nunes et al., 2016; Shanmugasundaram et al., 2013) and is also recommended in the Brazilian protocol for acute toxicity testing with earthworms (ABNT, 2014) as well as in the respective ISO standards (e.g. ISO, 1993, 1998). The use of tropical natural soils to evaluate pesticide effects is consistently increasing, as highlighted in a recent review focusing on soil ecotoxicology in Latin America (Niemeyer et al., 2017), and in three further studies (Kamoun et al., 2018; Oliveira et al., 2018; Owojori et al., 2019).

Despite this positive trend, the databases need to be substantially enlarged before a library of standard set of natural soils, representing different ecoclimatic tropical regions, can be setup (Niemeyer et al., 2017). Particular attention should be given on exploring the relationships between the soil properties and the observed toxicity effects in detail. The determined set of soils would be useful as reference soils in the environmental risk assessment of contaminated lands, and as standard soils for chemical toxicity testing (Buch et al., 2013; Kuperman et al., 2009; Oliveira et al., 2018).

5.2. Native tropical test species

Kuperman et al. (2009) identified the following criteria for the selection of tropical soil invertebrate species as suitable test organisms: 1) habitat – the species should occur in soils of the region of interest; 2) frequency and abundance – the species should frequently occur there in moderate to high numbers; 3) origin – the species should occur in, and ideally be native to the region of interest; 4) taxonomy – the species should be easy to identify; 5) practicability – the species should be easy to handle (e.g. small body size) and reproduce in the laboratory all year round (preferably as a mass culture); and 6) stress tolerance – the species should have low sensitivity to environmental factors but be sensitive to soil contaminants. Taking the often-limited resources in tropical countries into consideration, an additional criterion could be that screening tests should be simple and easy to conduct (Garcia et al., 2008). Following these criteria, Kuperman et al. (2009) identified the following locally-occurring earthworm, woodlouse, and millipede species: *Pontoscolex corethrurus* (Oligochaeta, Glossoscolecidae), *Circoniscus ornatus* (Isopoda, Scleropactidae) and *Trigoniulus corallinus* (Diplopoda, Pachybolidae).

5.2.1. Earthworms

Most earthworm tests conducted in tropical regions have used the temperate species *Eisenia fetida* and *E. andrei*. These species have limited ecological relevance for tropical areas, the more since they live in litter (epigeic) whereas tropical earthworm communities are predominated by endogeics (Brussaard et al., 2012; Hauser et al., 2012). Therefore, the use of tropical species in toxicity tests could contribute to a more relevant and reliable risk assessment of chemicals in these areas (Buch et al., 2013; De Silva et al., 2010a; De Silva et al., 2010b). The two mostly recommended tropical earthworm species for use in ecotoxicological testing are *P. corethrurus* and *Perionyx excavatus*, although their pesticide toxicity dataset remains slim (Buch et al., 2013; De Silva et al., 2010a; De Silva et al., 2010b; Niva et al., 2016). In addition, the life cycle of *P. corethrurus* lasts 12 months, and reproduction begins 90 days after maturity, making it impossible to use this species in chronic ecotoxicological tests, which usually do not run for longer than 56 days (Buch et al., 2011, 2013). On the other hand, this long life-cycle also dictates that this species may be exposed to pesticides for prolonged time periods, indicating the relevance of chronic test protocol development for this species.

While in temperate ecosystems earthworms are often the most important organisms governing OM breakdown, in the tropics not only earthworms but also microarthropods such as millipedes and woodlice seem to be the main driving force for the decomposition process (Förster et al., 2009 and references therein; Geissen and Guzman, 2006). Wiktelius et al. (1999) also indicated that other groups of organisms are involved in various processes in tropical countries than those known from the temperate region, e.g. termites as decomposers and ants as important general predators. Due to the different species composition of tropical soil ecosystems, test species representing those taxonomic groups especially relevant for tropical agroecosystem functioning should hence be included in tropical risk assessments. The same conclusion has previously also been reached for test species battery selection for aquatic tropical risk assessments (e.g. Daam and Rico, 2016; Moreira et al., 2016; OECD, 1998).

5.2.2. Enchytraeids

Enchytraeids have been indicated to be more abundant in temperate rainy climates with moderate or cold summers than in areas with dry, warm summers such as alpine meadows, tropical grasslands and tropical rainforests or in snowy areas and tundras (Brussaard et al., 2012). On the other hand, Schmelz et al. (2013) reported that enchytraeids occur worldwide in all soils with sufficient moisture, oxygen and nutrient supply, with densities in tropical regions comparable to those in temperate regions, suggesting that enchytraeids may be equally important for soil processes in both tropical and temperate regions (Schmelz et al., 2013). This discrepancy may at least partly be due to the fact that knowledge on their diversity and functioning in the tropics is not so well developed, mainly due to their small size, the difficulties of identification, and the general ignorance of this family (Brown et al., 2013; Schmelz et al., 2013). Although enchytraeid ecology and ecotoxicology is clearly biased toward studies in European temperate conditions, good examples of their use as test organisms and bioindicators are also present in tropical environments (e.g. Chelinho et al., 2012). This should motivate researchers worldwide to dedicate attention to these important but overlooked key players of soil food webs (Römbke et al., 2017). In Brazil, the enchytraeid reproduction test has already been standardized for tropical conditions (ABNT, 2012).

5.2.3. Isopods

From field studies in Amazonia it is known that woodlice (Isopoda) may dominate OM breakdown, especially in anthropogenically impacted sites like plantations (Höfer et al., 2001). Probably because of their low relevance in temperate agricultural soils, no test with any macro-saprophagous arthropod species has been standardized (Jänsch et al., 2005). However, the originally tropical isopod *Porcellionides pruinosus* has often been proposed and used as a test species in both temperate and tropical regions (e.g. Loureiro et al., 2005, 2009; Santos et al., 2011; Van Gestel et al., 2018). Other isopod species have also successfully been collected in tropical areas, cultivated under laboratory conditions and used in ecotoxicity (lethality and avoidance) tests (Da Silva-Júnior et al., 2014; Niemeyer et al., 2009, 2018c). Although these concern exotic species such as *Cubaris murina*, *Armadillidium vulgare* and *Porcellio dilatatus*, they play an important role in litter decomposition in anthropized tropical areas and may hence be considered as relevant isopod species for tropical ecotoxicity testing.

5.2.4. Collembolans

Knowledge on the effects of pesticides on tropical native edaphic species for taxonomic groups other than those addressed above remains scarce. For collembolans, the temperate species *Folsomia candida* has often been used in tropical testing (e.g. Alves et al., 2014; Garcia, 2004; Natal-da-Luz et al., 2012; Oliveira et al., 2018; Zortéa et al., 2015, 2018a). However, at least in the laboratory other springtail species have been identified that are as suitable as *F. candida* in terms of practicability, sensitivity etc, but which do prefer higher temperatures. The most commonly used "tropical" species seems to be *Sinella curviseta*, which has been tested with different insecticides and fungicides under different soil moisture and temperature conditions (Bandow et al., 2014a, 2014b). The collembolan *Proisotoma minuta* also occurs in tropical areas and has been successfully collected in Brazil and cultivated under laboratory conditions both at 20 and 24 °C (Buch et al., 2016). Despite that *F. candida* was more sensitive to mercury than *P. minuta* (Buch et al., 2016), the latter species showed higher sensitivity to mineral oil (used as adjuvant in herbicide application) than *F. candida* (De Santo, 2018).

5.2.5. Mites

Regarding oribatid mites, the pantropical oribatid mite *Archegozetes longisetosus* has been proposed as a tropical laboratory test species because of its easy cultivation in the laboratory and quick development (Heethoff et al., 2013). On the other hand, this species is not commonly found in forest and agricultural soils in field experiments and is not widespread throughout the tropics, a condition required for the species to be a generic standard test species for tropical areas (Kuperman et al., 2009). Previous research has shown that at least seven common species of oribatid and gamasid mites in a Nigerian forest can survive several days in the laboratory when fed on yeast (Badejo and Akinwole, 2007). Recently, a laboratory culture of one of these seven species, *Muliercula inexpectata*, was installed and toxicity tests were successfully conducted evaluating Cd and dimethoate toxicity under tropical conditions (26 °C; natural tropical soil; Owojori et al., 2019). Species belonging to the genus *Muliercula* are well distributed in Nigeria (Shtanchaeva et al., 2014), and have frequently been reported in other parts of Africa and Brazil (Badejo et al., 2002; Coetzer, 1968).

5.2.6. Termites, nematodes and beetles

Termites have been discussed to play an important role in OM decomposition in especially tropical African and Australian soils, but their sensitivity towards pesticide stress has hardly been studied (Brussaard et al., 2012; De Silva et al., 2010a). Laboratory studies on the effects of pollutants on soil nematodes, which have been demonstrated to be involved in the nitrogen cycling in tropical soils (Villenave et al., 2004), have been mainly focused on heavy metal toxicity in temperate systems (Chelinho et al., 2011a). However, the sensitivity of tropical nematode populations to chlorpyrifos has recently been reported (Kumar et al., 2017). Also, the toxicity of pesticides to indigenous beetles (Coleoptera) is practically unknown (Martínez et al., 2011).

5.3. Developing tropical toxicity test guidelines

As also discussed above, very few standardized ecotoxicological tests have been performed assessing pesticide toxicity to tropical indigenous soil invertebrates (Brown et al., 2013; De Silva, 2009; Garcia et al., 2011; Niemeyer et al., 2017; Niva et al., 2016). Most soil ecotoxicity studies, even when conducted in tropical areas, have generally been conducted using a series of invertebrate species originally found in temperate environments (Niemeyer et al., 2017; Römbke et al., 2008). According to Niva et al. (2016), seven standard test guidelines concerning soil quality have so far been published by ABNT (*Associação Brasileira de Normas Técnicas*) in Portuguese in Brazil. With the exception of the guideline on acute toxicity testing with earthworms (ABNT, 2014), all others are translations of ISO guidelines but with a note recommending the use of the tropical artificial soil and a temperature adaptation (Niva et al., 2016). Similarly, two revised ISO guidelines on acute and reproduction toxicity tests with *Eisenia fetida/Eisenia andrei* now contain an Annex A that describes testing under tropical conditions, including to replace the amount of OM (10% or, if changed in general, 5%) by coir dust or composted coconut peat and performing tests at higher temperatures (26–28 °C) and in clayey soils (Nunes et al., 2016). Subsequently, none of these guidelines make any recommendation on the use of local test species (Niemeyer et al., 2017; Niva et al., 2016) as has for example been done over two decades ago for fish (OECD, 1992) and tropical aquatic test species in general (OECD, 1998). Further tests and standardization are necessary for native, particularly soil-dwelling and feeding (geophagous) tropical species to increase the ecological relevance of tropical toxicity evaluations (Brown et al., 2013; Niemeyer et al., 2017; Niva et al., 2016; Owojori et al., 2019).

Bartz et al. (2013) built a classification of the biological soil quality of tropical agroecosystems based on earthworm density and species richness based on literature data together with those on earthworm populations sampled in six watersheds in SW Paraná State, Brazil. They noted that the FAO manual scores for good (> 30 worms of preferably 3 or more species), moderate (15–30 and preferably 2 or more species) and poor (< 15 and predominantly 1 species) involve much higher earthworm abundance and slightly lower earthworm diversity per sample than those proposed in their "tropical" classification. Therefore, they concluded that the use of abundance values obtained from temperate climate regions such as Europe or New Zealand in warm tropical climates is not reasonable and may lead to erroneous interpretations of soil quality (Bartz et al., 2013). There is hence a need for gathering of enough data from various ecosystems, in particular soil/climate data, so that reference values can be proposed as to what abundance and diversity is poor, adequate, good and excellent in terms of earthworm populations for each context (Bartz et al., 2013; Brown et al., 2013).

Earthworm avoidance tests have frequently been proposed as an initial screening tool for prospective and retrospective risk assessment of pesticides in the tropics due to their easy execution and general high sensitivity (Alves et al., 2013; De Silva and Amarasinghe, 2008; De Silva and Van Gestel, 2009b; De Sousa and de Andréa, 2011; Garcia et al., 2008; Nunes and Espíndola, 2012). Endpoints generated through avoidance tests by De Silva and Van Gestel (2009b) were more sensitive than survival but less sensitive than reproduction. Subsequently, these authors recommended that this should be further confirmed to evaluate to what extent earthworm avoidance tests can also replace chronic exposure tests as an initial screening tool for risk assessment (De Silva and Van Gestel, 2009b).

5.4. Developing methods and procedures for higher tier testing

Over two decades ago, Lacher and Goldstein (1997) already indicated that single species toxicity testing may be of limited value in the tropics since diversity is extremely high and most species of vertebrates are found at much lower densities than is typical for temperate zone species. Subsequently, tropical field and semi-field studies have frequently recommended for evaluating i) the direct effects of pesticides on community-level; ii) indirect effects on ecosystem functioning; and iii) the recovery potential of field communities (e.g. Chelinho et al., 2014; De Silva et al., 2010a; Förster et al., 2006; Hairiah et al., 2001; Kuperman et al., 2009; Niva et al., 2016; Peveling et al., 1999). Especially, the use of bait-lamina sticks to assess soil fauna feeding activity in higher-tier studies has been proposed as a relevant tool for ecological assessments and has successfully been tested in tropical soils (Niemeyer, 2012; Römbke et al., 2006). Their usefulness as a screening test under field conditions was also recently proven in a study with different formulations of glyphosate (Niemeyer et al., 2018b).

Regarding semi-field studies, Förster et al. (2006, 2009) reported that they conducted the first terrestrial model ecosystem (TME) studies ever under tropical conditions. From a technical point of view, the TME test method could be applied without problems and without any relevant methodological modifications from the method developed under temperate conditions (Förster et al., 2006). These authors further indicated that future studies are needed to clarify whether a refined control of the microclimatic conditions, e.g. by irrigating the soil cores more frequently and via special rain heads (Knacker et al., 2004), and by using mixed litter material and individuals from synchronized cultures (Jänsch et al., 2005), could help reduce mortality of the soil fauna introduced into TMEs (Förster et al., 2006). So far, few additional TME studies have been conducted under tropical conditions and they have focused on pesticide fate (e.g. Bicalho and Langenbach, 2013; Getenga et al., 2009; Langenbach et al., 2000) or effects of organic residues on soil fauna (Segat et al., 2019). Thus, the applicability of TMEs to evaluate pesticide effects under tropical conditions remains largely unknown.

Tropical field studies have more often successfully been conducted to evaluate environmental side effects of land-use practices in all tropical continents (e.g. Norgrove, 2007; Piola et al., 2009; Santos et al., 2018; Souza et al., 2012; Susilo et al., 1994; Swift and Bignell, 2001). Field studies have the advantage over laboratory and semi-field studies that they provide the highest level of ecological realism, both in terms of fate and effects. Langenbach et al. (2000), for example, reported lower volatilization rates in microcosms than in the field, where solar radiation enhances soil temperature and increases volatilization (Langenbach et al., 2000). On the other hand, due to their higher levels of complexity and variability, interpretation of field effects is often hampered (e.g. De Silva et al., 2010a). Förster et al. (2006), for example, could not demonstrate effects of lambda-cyhalothrin on the abundance of field litter- and soil-dwelling arthropods, and they attributed this to the high variability in abundance values.

Due to their high biodiversity, spatio-temporal variation and low abundances discussed above (Förster et al., 2006; Lacher and Goldstein, 1997; Santos et al., 2018), simplified methods have been proposed to evaluate soil invertebrate communities in tropical agricultural fields. Peveling et al. (1999), for example, proposed an assessment of the impact of biological and chemical grasshopper control agents on ground-dwelling arthropods in Niger based on presence/absence sampling. However, also this method may be hampered due to the general lack of taxonomic capacity in tropical countries and the absence of a large body of trained taxonomists worldwide for many of these organisms, especially some of the lesser-known groups (Brown et al., 2013). Chelinho et al. (2011b, 2014) proposed the use of a trait-based approach to establish ecotoxicological responses in field communities from different geographical regions. Environmental risk assessment based on ecological/functional traits (TERA—Trait-Based Risk Assessment) advocates the use of morphological/physiological/ecological characteristics of organisms to describe the effects of toxic substances or other stress factors at the community level, in terms of species abundance, diversity, distribution and interactions with other species and the environment (Baird et al., 2008). Chelinho et al. (2011b, 2014) successfully applied this approach for tropical terrestrial risk evaluations and hence concluded that the evaluation of pesticide effects based on traits is a promising tool and an easier alternative than the taxonomic approach for tropical areas. Suthar (2014) noted a lower sensitivity of an epigeic tropical earthworm species to methyl parathion than the tropical endogeic and anecic earthworm species they tested. Since cutaneous absorption and dietary intake are the two main mechanisms of pesticide uptake by soil organisms, epigeics may have an advantage over burrowing earthworms due to their surface-dwelling mode of life (Langdon et al., 2001; Suthar, 2014). The use of traits may hence increase our understanding of the biology of tropical soil organisms and to determine sensitive test species based on their traits.

6. Sensitivity

As was discussed in section 2, tropical ecotoxicological research has increased in the past years (Fig. 1). However, the available toxicity dataset for tropical soil organisms remains limited, hampering sensitivity comparisons with their temperate counterparts. Sensitivity comparison evaluations made for the aquatic compartment also concluded that the tropical dataset was limited, although comparisons could be made both using the species sensitivity distribution (SSD) approach and the model ecosystem approach (e.g. Daam and Van den Brink, 2010, 2011; Rico et al., 2011; Sanchez-Bayo and Hyne, 2011). Although these studies found cases of different sensitivities, they generally concluded that there was no consistent trend of a greater or smaller sensitivity of tropical aquatic organisms as compared to temperate species. For example, Raymundo et al. (2019) recently did not find sensitivity differences between temperate and tropical cladocerans to the insecticide chlorpyrifos.

Daam et al. (2011) compared the sensitivity of *E. fetida* to pesticides with that of other soil invertebrates, regardless of their climatic origin. To this end, they mined toxicity data from the US Environmental Protection Agency (US-EPA) ECOTOX database (http://cfpub.epa.gov/ecotox/), the largest database of its kind available. Due to a great variety in threshold value types and their units, as well as the under-representation of various taxonomic groups (especially insects), they could not construct "traditional" SSDs, i.e. based on different taxa with the same threshold type and unit for the same compound. Subsequently, Daam et al. (2011) used the relative tolerance (Trel) approach, i.e. the ratio between the toxicity value of a certain species by that of *E. fetida*, as to allow incorporating toxicity data of different pesticides in a single SSD curve. Given the overall low data availability for tropical soil invertebrates, we used the same approach to construct an SSD comparing the sensitivity of the tropical earthworm *P. excavatus* to several pesticides with that of *E. fetida* (Fig. 3). To minimize any possible influence of inter-laboratory variation on this analysis, when possible the toxicity data for *E. fetida* were taken from the same publication reporting those for *P. excavatus*. In case that more than one toxicity value

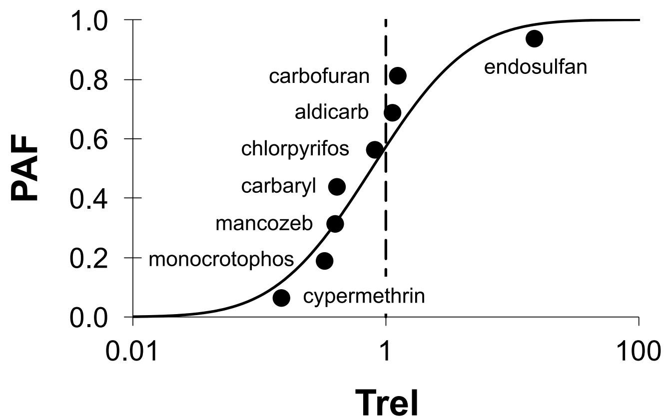

Fig. 3. Species sensitivity distribution (SSD) comparing the sensitivity of the tropical earthworm *Perionyx excavatus* to pesticides with that of *Eisenia fetida* sensu lato using the relative tolerance (Trel) approach. The vertical dashed line at Trel = 1 indicates the sensitivity of *E. fetida* sensu lato. Trel < 1 and Trel > 1 indicate a higher and lower sensitivity of *P. excavatus* relative to *E. fetida* sensu lato, respectively. PAF = potentially affected fraction. Source data: De Silva et al., 2009; das Gupta et al. 2010; De Silva et al., 2010b).

was published for the same endpoint/species in the same publication, the geometric mean was taken.

As can be deducted from Fig. 3, *P. excavatus* appears to be more sensitive than *E. fetida* for the majority of compounds, whereas similar (aldicarb and carbofuran) and a lower (endosulfan) toxicity were also denoted. In line with this, several toxicity studies revealed a greater sensitivity of tropical soil organisms as compared to temperate counterparts (e.g. Chelinho et al., 2014; De Silva et al., 2010b; Nunes et al., 2016). For example, Römbke et al. (2007) noted an acute-to-chronic ratio (ACR) up to 167 in earthworm tests when performed under tropical conditions, whereas the ACR was about 10 under temperate conditions. This greater toxicity to tropical species has been attributed to a greater uptake rate (especially through the skin) of pesticides as a result of the humid and warmer conditions in the tropics and a higher activity of tropical soil invertebrates (e.g. De Silva et al., 2010a; Förster et al., 2006; Niemeyer, 2012; Römbke et al., 2007). A similar toxicity to pesticides between temperate and tropical soil organisms has also previously been reported, e.g. in the TME study by Förster et al. (2006) and between the tropical *P. corethrurus* and the temperate *E. andrei* (Buch et al., 2013). Also, relatively lower sensitivity of tropical organisms has previously been reported, which is generally ascribed to lower exposure levels (see section 3) and/or faster metabolism leading to faster elimination processes (e.g. De Silva et al., 2010b; De Silva and Van Gestel, 2009b; Römbke et al., 2007).

From the above, it can be concluded that sensitivity comparisons do not indicate a consistent similar, greater or lower relative sensitivity of tropical soil organisms. In addition, it should be noted that differences are generally small, especially considering that toxicity values from the same test system, using the same chemical but performed in different laboratories, may vary by a factor of up to five (Moser et al., 2009) or even ten (Römbke and Moltmann, 1996). In addition, different tropical soil earthworm species evidently also differ in their intrinsic sensitivity to pesticides (e.g. Patnaik and Dash, 1993). In this context it should be noted that formulations may affect organisms differently from the active ingredients, which may also behave differently under tropical conditions (De Santo et al., 2018).

It may be concluded that the relatively small differences in toxicity denoted in studies comparing the sensitivity of temperate and tropical soil organisms appear to depend to a large degree on i) the pesticide evaluated (and its form, i.e. active ingredient or formulated product); ii) the adopted experimental design (e.g. soil type, environmental conditions, test duration, endpoint), and iii) intrinsic sensitivity of the species tested (Alves et al., 2013; Buch et al., 2013; De Silva et al., 2010b; De Silva and Van Gestel, 2009b; Garcia et al., 2011; Kreutzweiser et al., 2008; Niva et al., 2016; Nunes et al., 2016; Römbke et al., 2004, 2007; Zortéa et al., 2018b). In addition, species diversity and abundance of soil invertebrates may also vary under tropical conditions making prediction of eventual differences in effects on (semi-) field levels even more difficult (De Silva et al., 2010b). The use of a set of standard tropical test soils to evaluate the sensitivity of a set of native tropical test species has therefore frequently been recommended (c.f. section 4 and references therein).

7. Concluding remarks and way forward

From the above, it may be deducted that pesticide fate and effects may be very different in tropical areas as compared to their temperate counterparts. More terrestrial ecotoxicology research is hence needed in the tropics, especially in those tropical areas and countries that have little research efforts to date. Field studies in tropical agroecosystems are needed to develop and calibrate environmental fate model scenarios simulating tropical conditions. Tropical toxicity test methods need to include 1) the identification of tropical natural soils to be used as reference test substrates; 2) the evaluation of native test species to be used as tropical standard test species; 3) the development of test guidelines and procedures applicable to tropical/subtropical conditions, including higher tier testing. In addition, testing biomarkers after pesticide stress may aid in deducting the underlying toxic mechanisms in tropical test organisms and evaluate possible differences with their temperate counterparts (Constantini, 2015).

Pesticide application rates and practices in tropical areas were also discussed above to lead to a greater pesticide risk in real-world agricultural settings than in their temperate counterpart. The increase in training and awareness programs on pesticide use for farmers has therefore been advocated, although it is also recognized that such programs may not effectively translate into behavioral changes (Yuantari et al., 2015). The establishment of soil quality standards and prospective risk assessment schemes should also be a priority, especially for the old pesticides. In Brazil, the states of São Paulo and Minas Gerais already defined soil prevention and intervention values for organochlorine pesticides, among other contaminants (CETESB, 2014; COPAM, 2011).

One example for improving the situation is a recent activity of the United Nations Food and Agriculture Organization (FAO). It focuses on the identification of appropriate methods and procedures to evaluate the risks of pesticides to soil organisms and soil functions, intended for pesticide registration in low and middle-income countries. The FAO ad-hoc working group developed an environmental risk assessment scheme adapted for the specific needs of tropical countries (Fig. 4; FAO, 2018). According to this workgroup, no new first tier toxicity tests need to be developed, but existing tests need to be adapted to tropical or (semi-) arid situations in terms of soils and test conditions. Soil mesofauna communities, and hence the potential side-effects of pesticides, are known to vary in different tropical agroecosystems (Zagatto et al., 2017). Studies are hence needed to support guidance of what can be considered comparable agroecological zones aiding regulators to conduct bridging, i.e. an assessment approach by which a risk assessment conducted in one country (the “reference country”) is interpreted and applied to another situation (FAO, 2018).

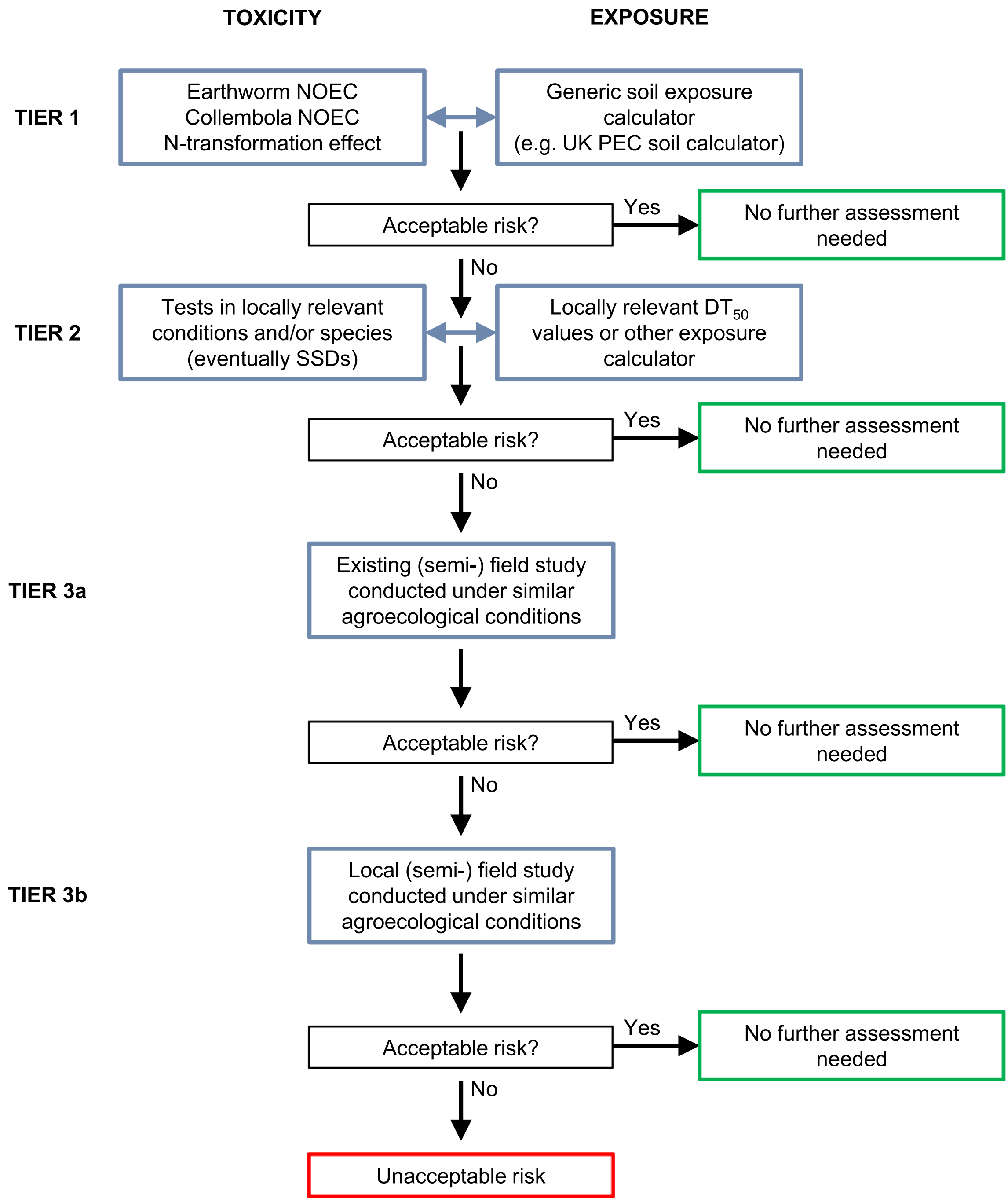

Fig. 4. Risk assessment framework for tropical soil organisms and processes as proposed by the FAO Working group (adapted from FAO, 2018).

Declarations of interest

None.

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